Direct and Strong Evidence of Aerosol Effects on Cloud & Precipitation from Long-term ARM Ground & A-Train Satellite Measurements

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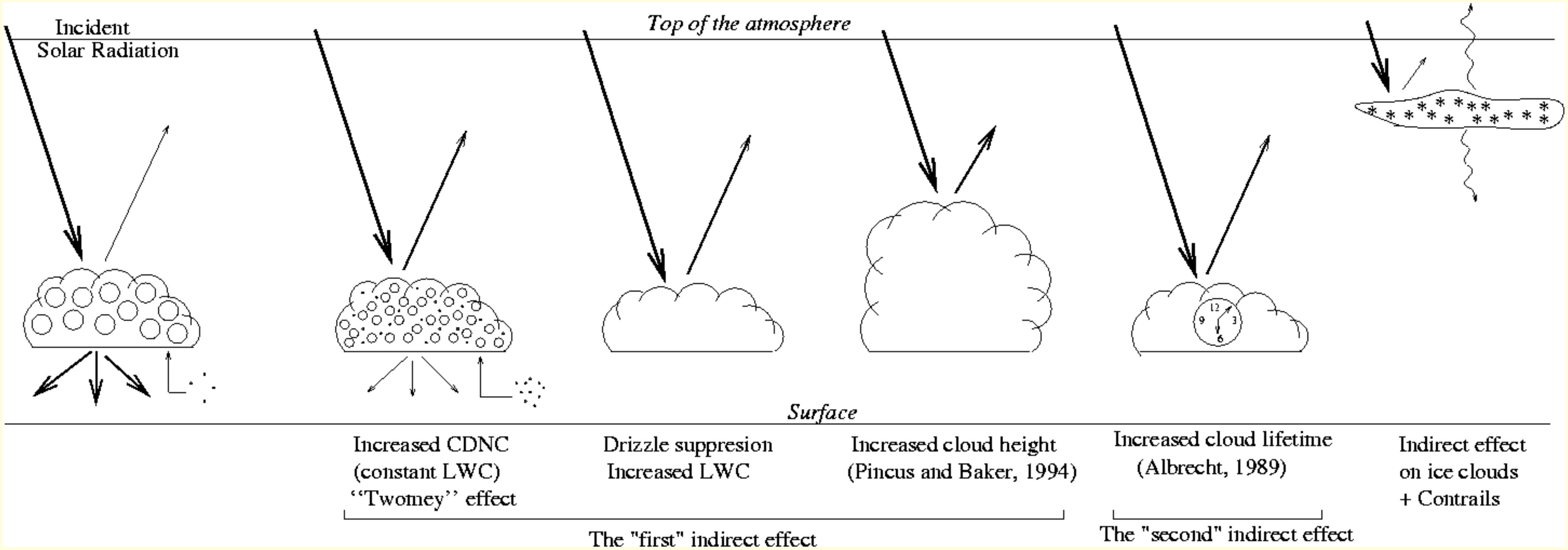
Indirect Effect

Haywood and Boucher *Revs. Geophys.* **2000**



1) **Increased CCN - reduces r_{eff}**

2) **Drizzle suppression - increases LWC**

3) **Increased cloud height**

4) **Increased cloud lifetime**

'First' indirect effect

$$\tau \sim \frac{3\,LWP}{2\,r_{eff}}$$

'Second' indirect effect

A lot have been done concerning aerosol's impact on rainfall

Rainfall Suppressed by Aerosols

Rainfall Enhanced by Aerosols

Observational studies

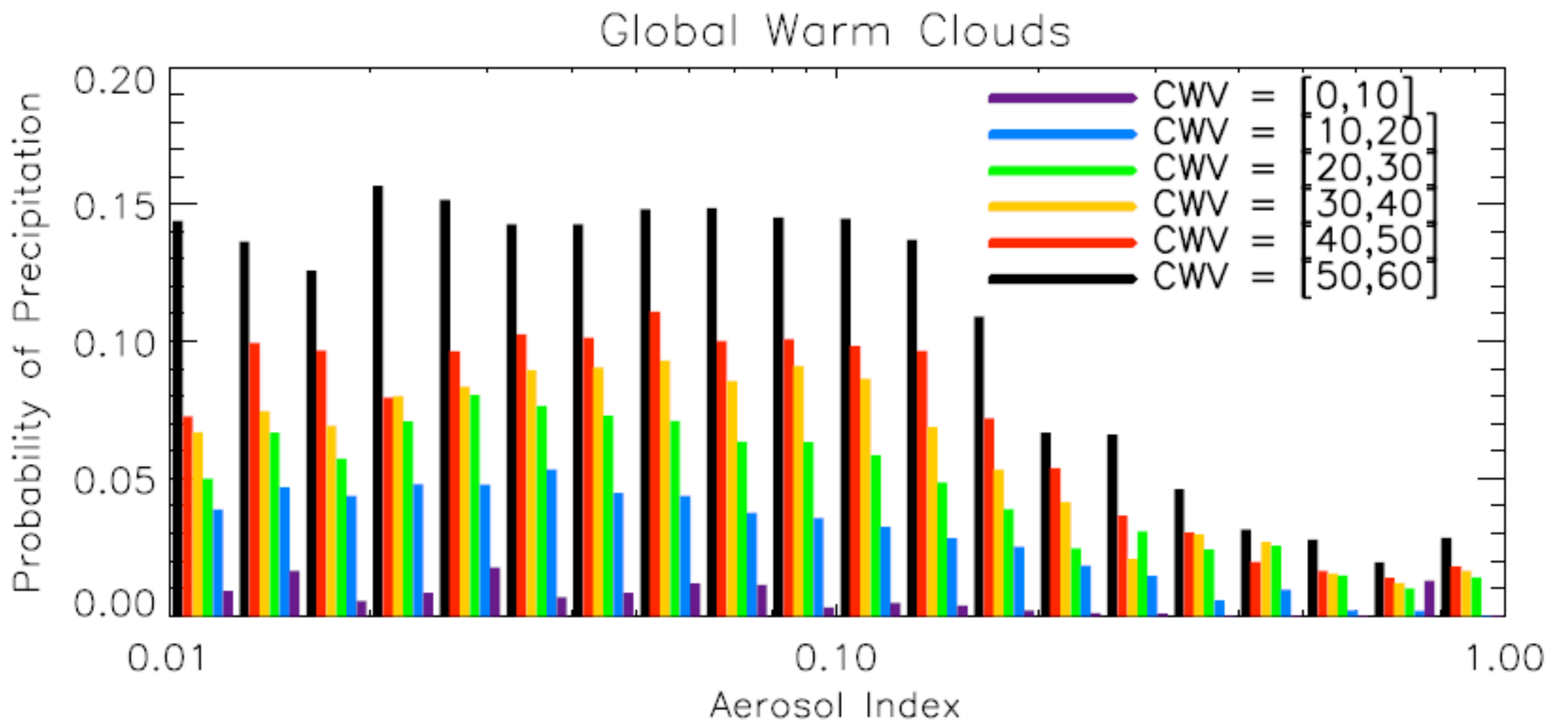
Rosenfeld, 1999;
Rosenfeld, 2000;
Andreae, 2004;
etc

Koren, 2005;
Lin, 2006;
Bell, 2007;
etc

Modeling studies

Khain, 2004，2005;
Tao 2007, Fan, 2007;
Van den Heever, 2007
etc

Probability of Warm Cloud Precipitation



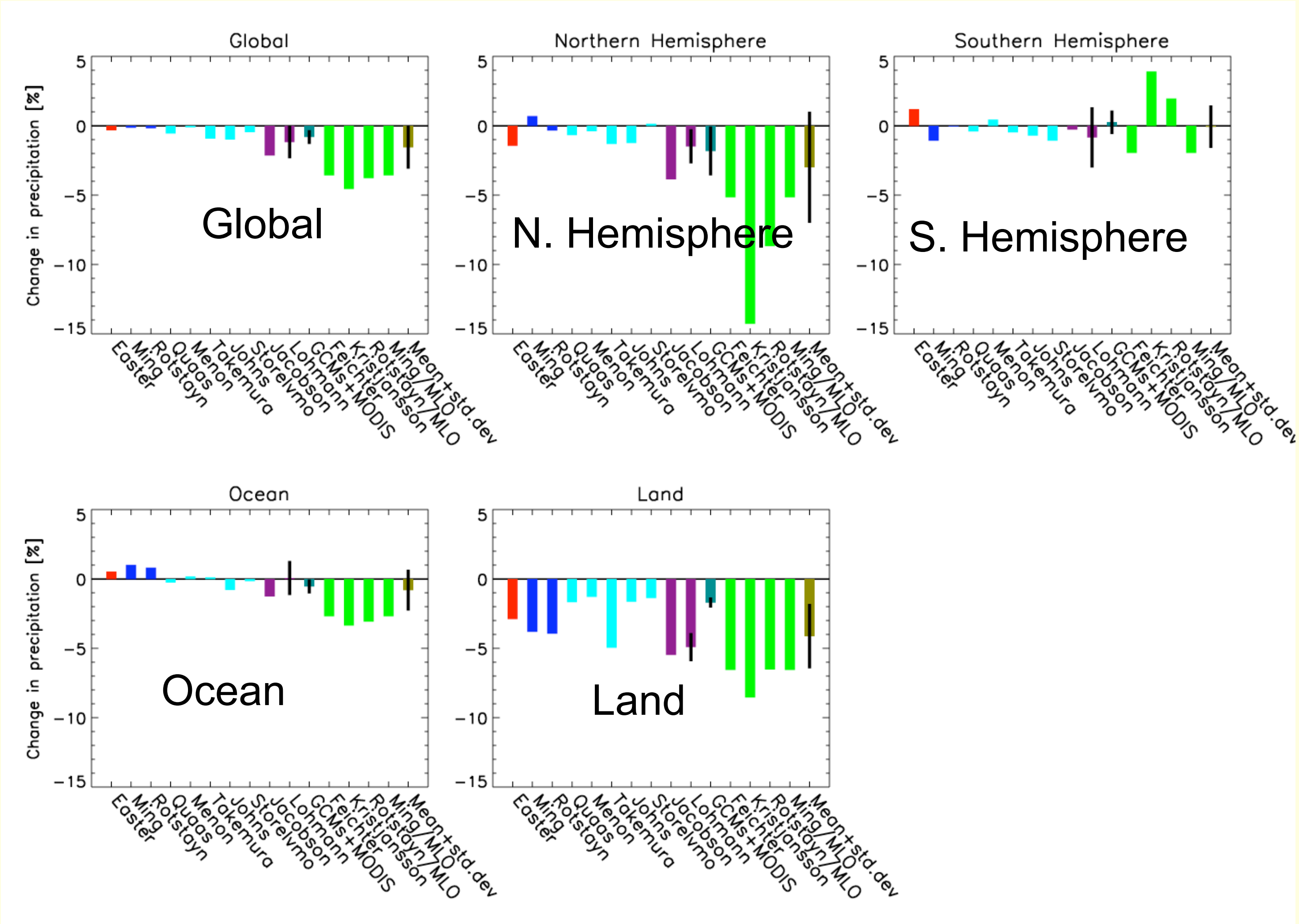
Global probability of warm cloud precipitation as a function of AI for Various column water vapor regimes. The units for CWV are kg/m2

[Lebstock, et al, 2008]

Global effects of pollution on precipitation

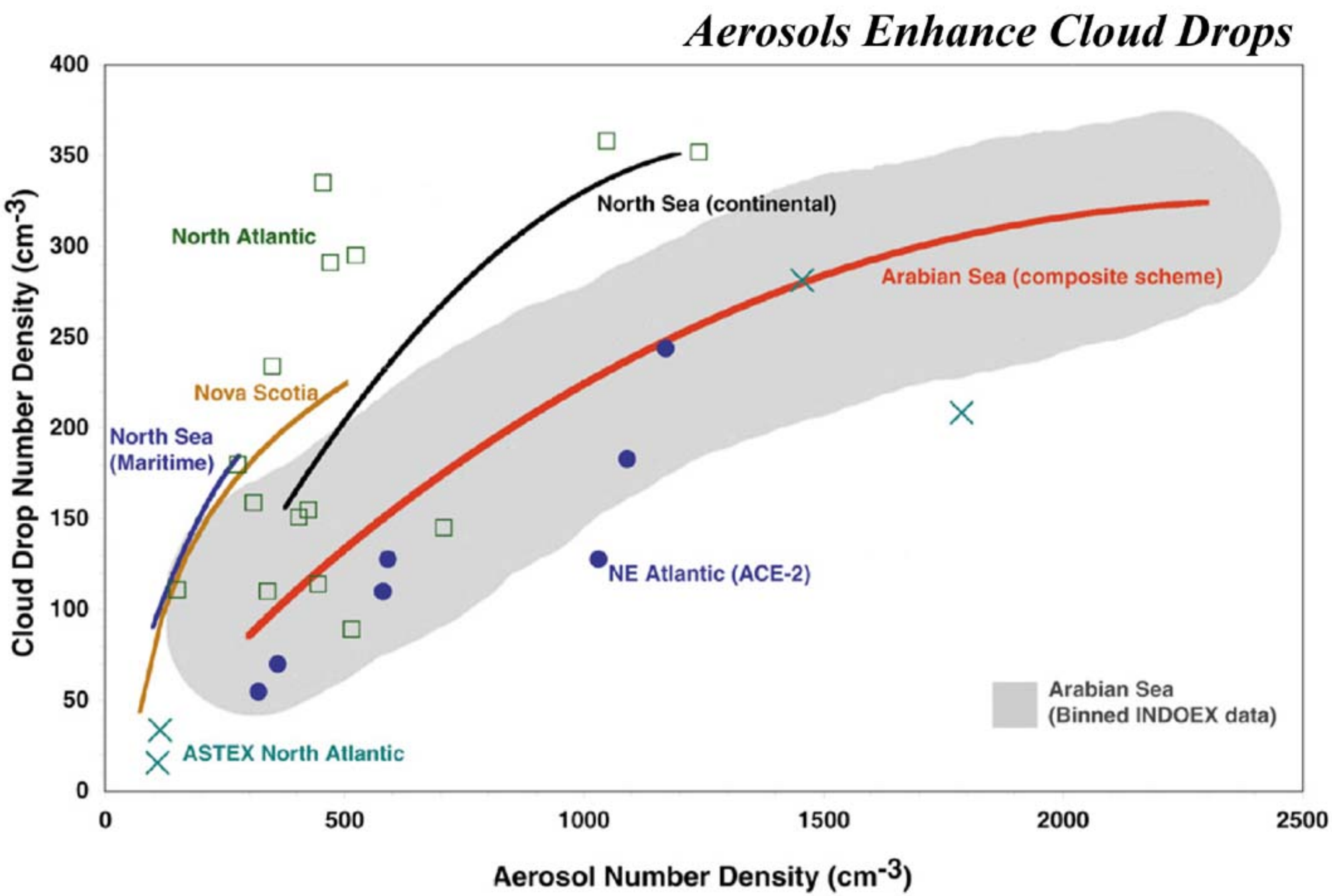
GCM-- estimates 0 to - 4.5% change in global mean precipitation over the last 100 years due to the direct and indirect aerosol effects.

The differences among models over land range from -1.5% to -8.5%.

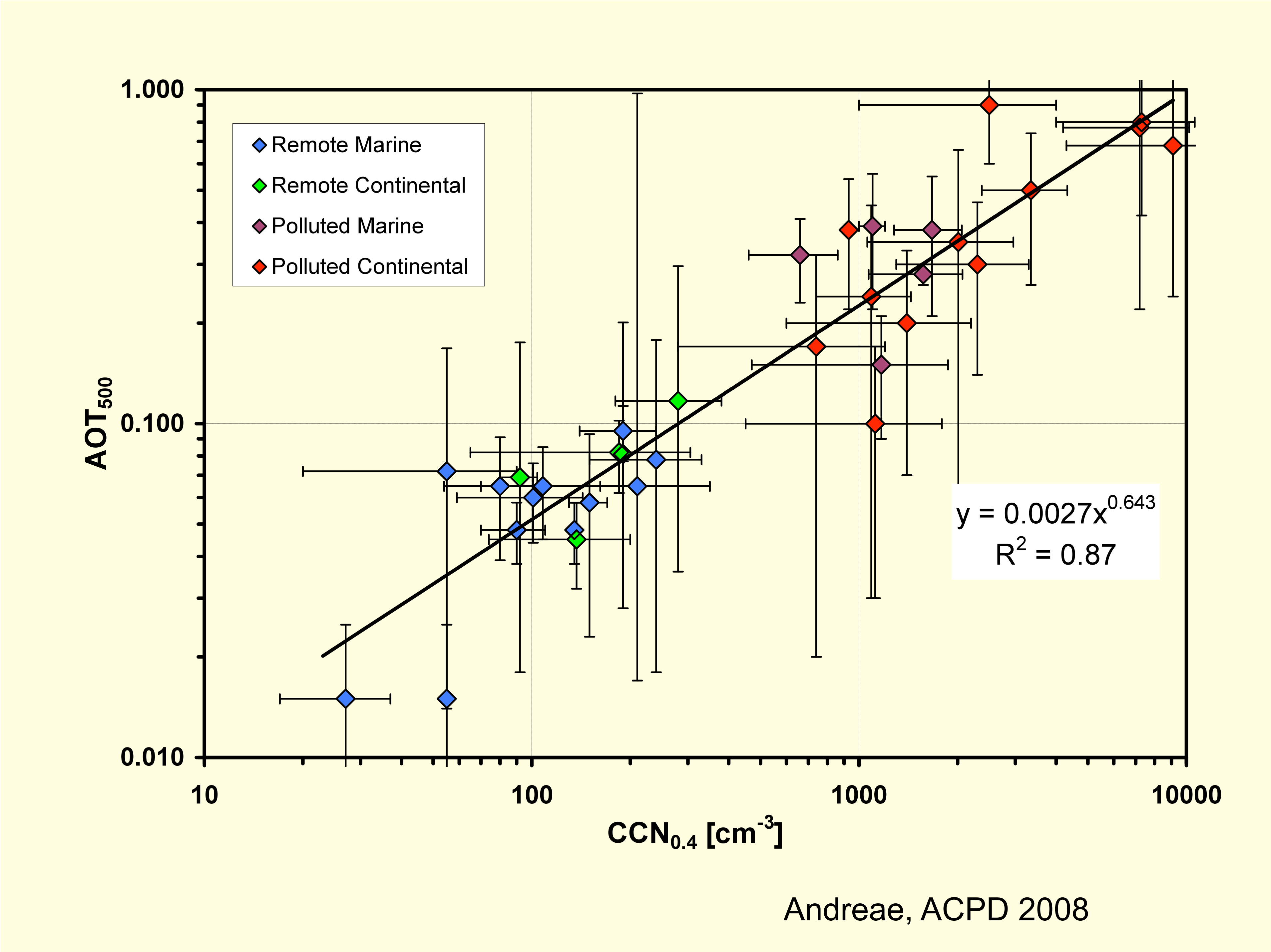


Aerosol Microphysical Effect
(Twomey Effect &
Apparent Anti-Twomey Effect)

Fig. 2. In-situ Measurements of Aerosols and Clouds

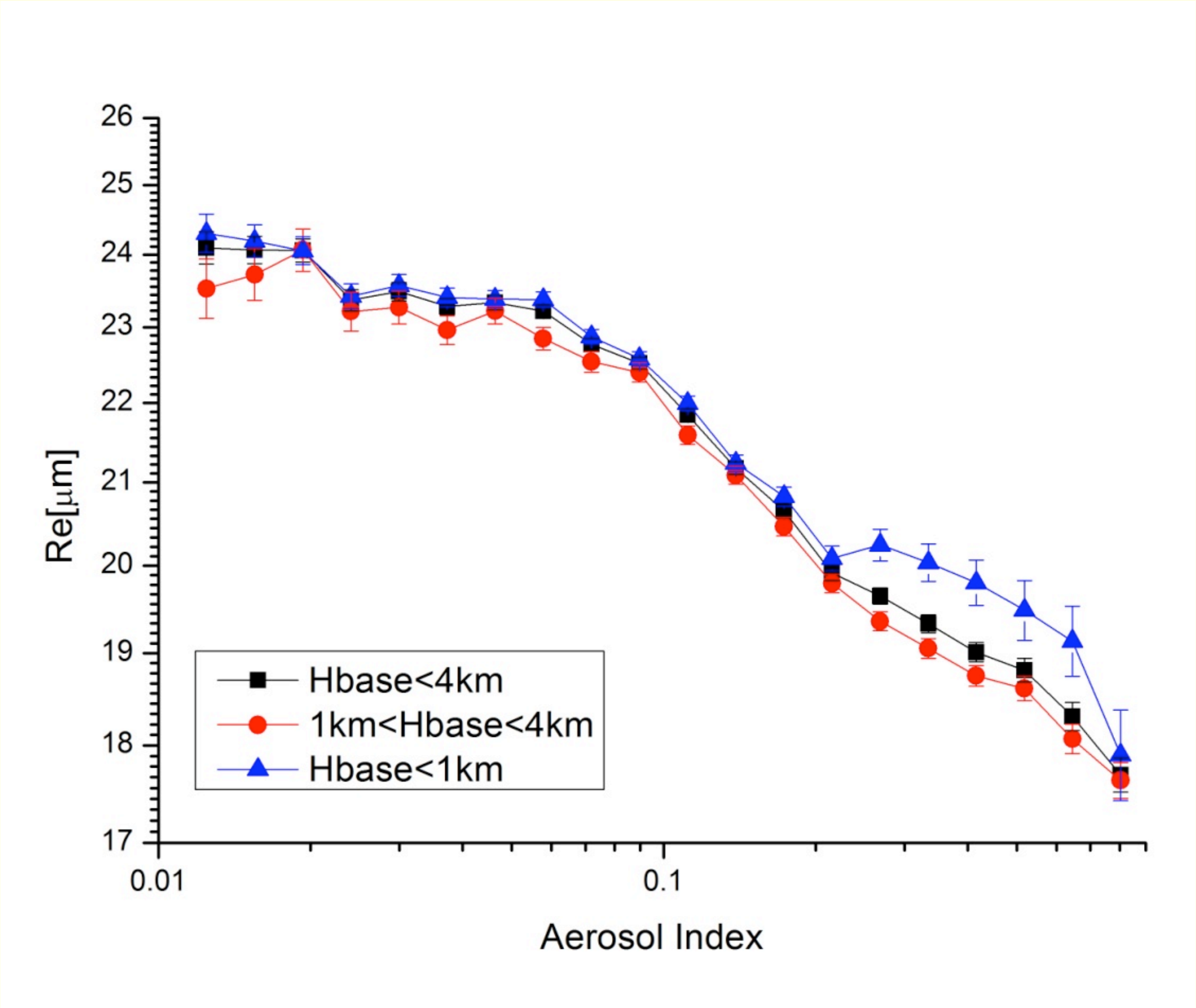


Ref: Ramanathan, Crutzen, Kiehl and Rosenfeld, *Science* 2001.

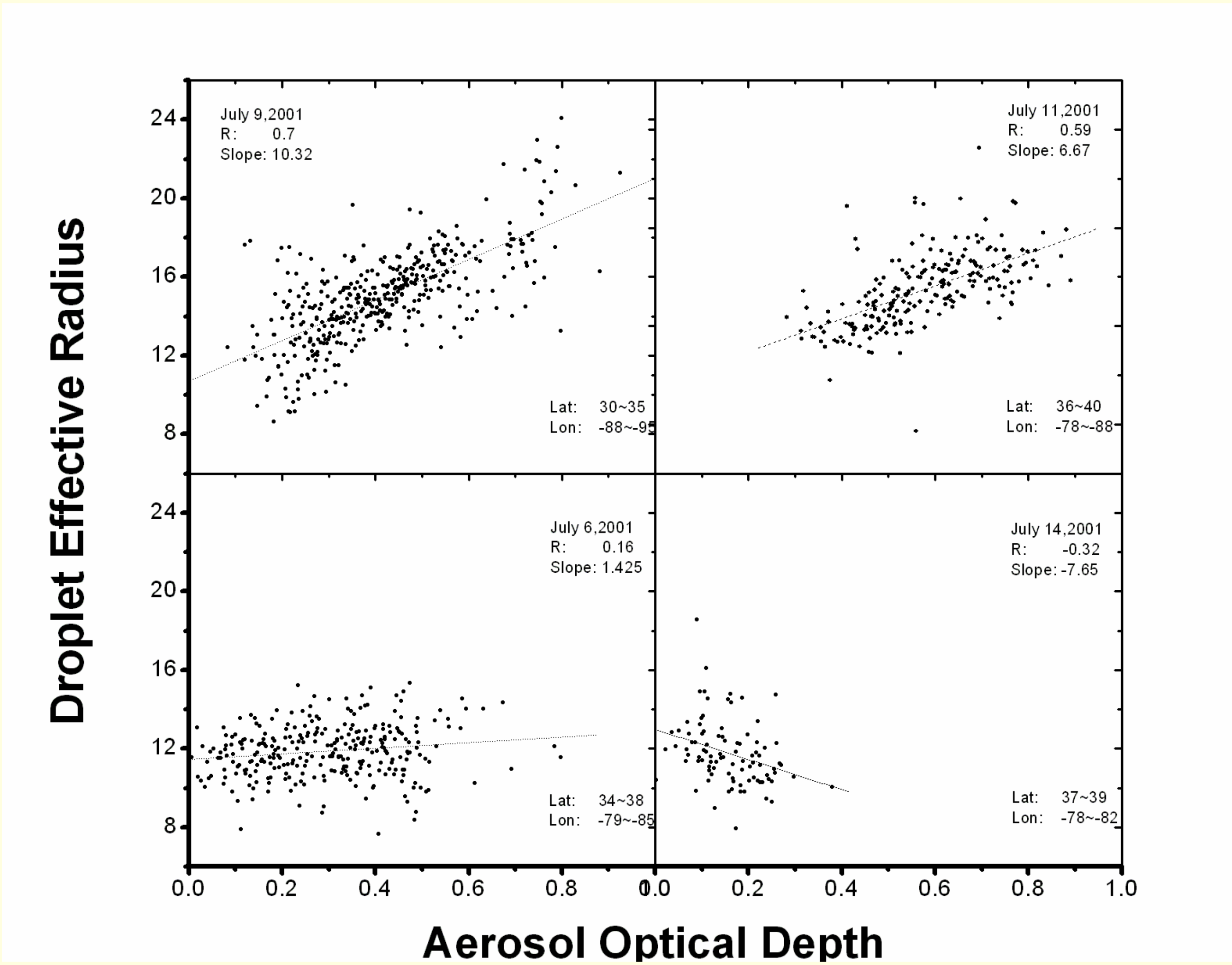


Remote Marine
Remote Continental
Polluted Marine
Polluted Continental
$y = 0.0027x^{0.643}$
$R^2 = 0.87$
1.000
0.100
0.010
10
100
1000
10000
AOT_{500}
$CCN_{0.4}$ [cm^{-3}]
Andreae, ACPD 2008

Aerosol Impact on Cloud Particle Size

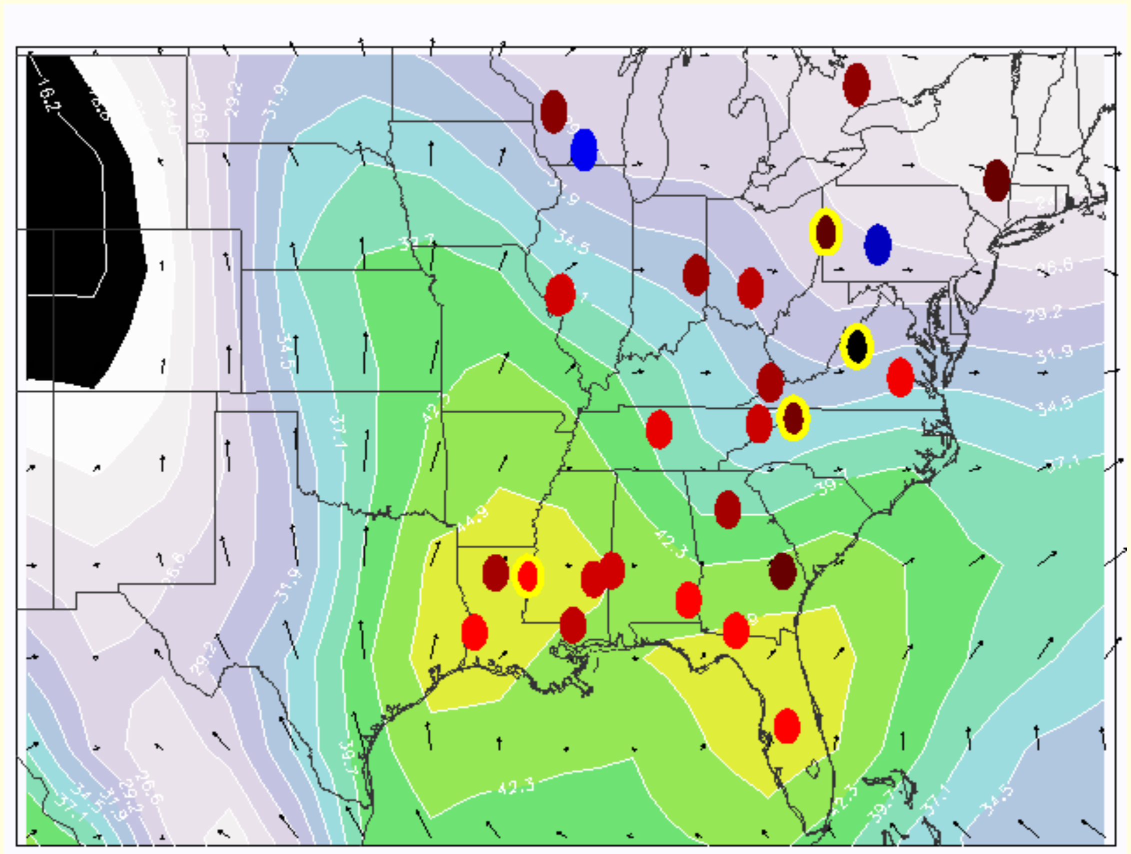


DER-AOD relationship



Yuan et al. (2008, JGR)

AIE efficiency distribution



Yuan et al. (2008)

Global Analysis

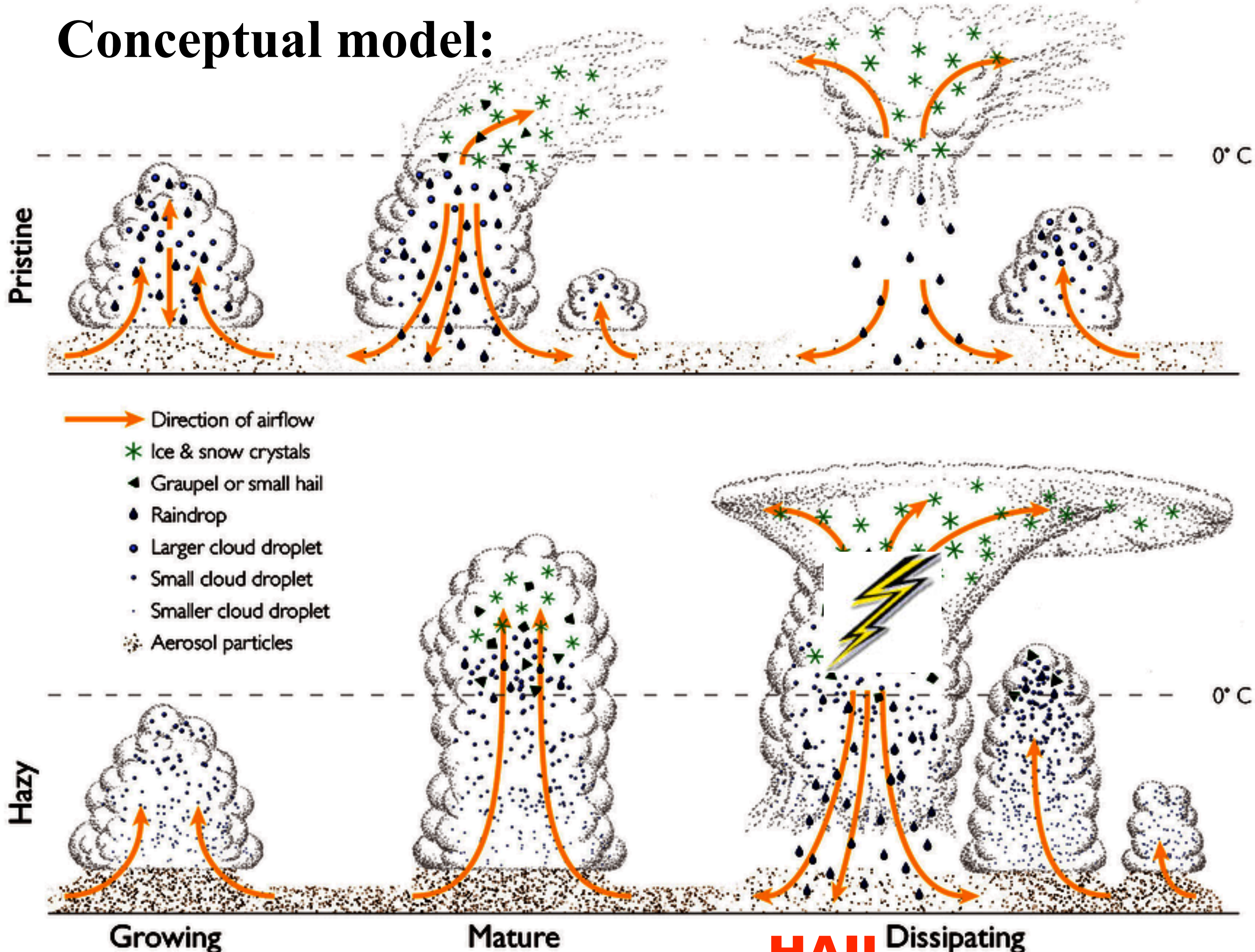
Region	Latitude range	Longitude range	Dominant Aerosol/Cloud Types	Period	AIE efficiency	Sample size
North Atlantic	10-20N	20-40 W	Dust, Stratocumulus	June-August, 2002	Negative	99,978
South Atlantic	5-20S	5E-20W	Smoke, Stratocumulus	June-August,2002	Negative	100,377
Southern Pacific	5-25S	75-105W	Sea salt, sulfate and pollution, Stratocumulus	August-October, 2002	Negative	74,216
Indian Ocean	12-20N	60-70E	Dust with pollution, Trade cumulus	June-August, 2002	Negative	94,023
India	13-24N	70-85E	Mixture of sulfate, dust, sea salt and smoke, cumulus	June-August,2002	Neutral	53,888
Amazonia	8S-12N	44-76W	Mainly smoke	August-October, 2002	Negative	672,421
Southeastern China	23-43N	100-120E	Mixture, cumulus	June-August,2002	Positive	179,533

Student-t test indicates except India the difference among different loading of aerosols are statistically significant at least at the 95% level

Yuan et al (2008)

Aerosol Thermodynamic Effect (Invigoration effect, but not just for ice clouds)

Conceptual model:



Rosenfeld et al. (2008)

Graphics by Robert Simmon, NASA

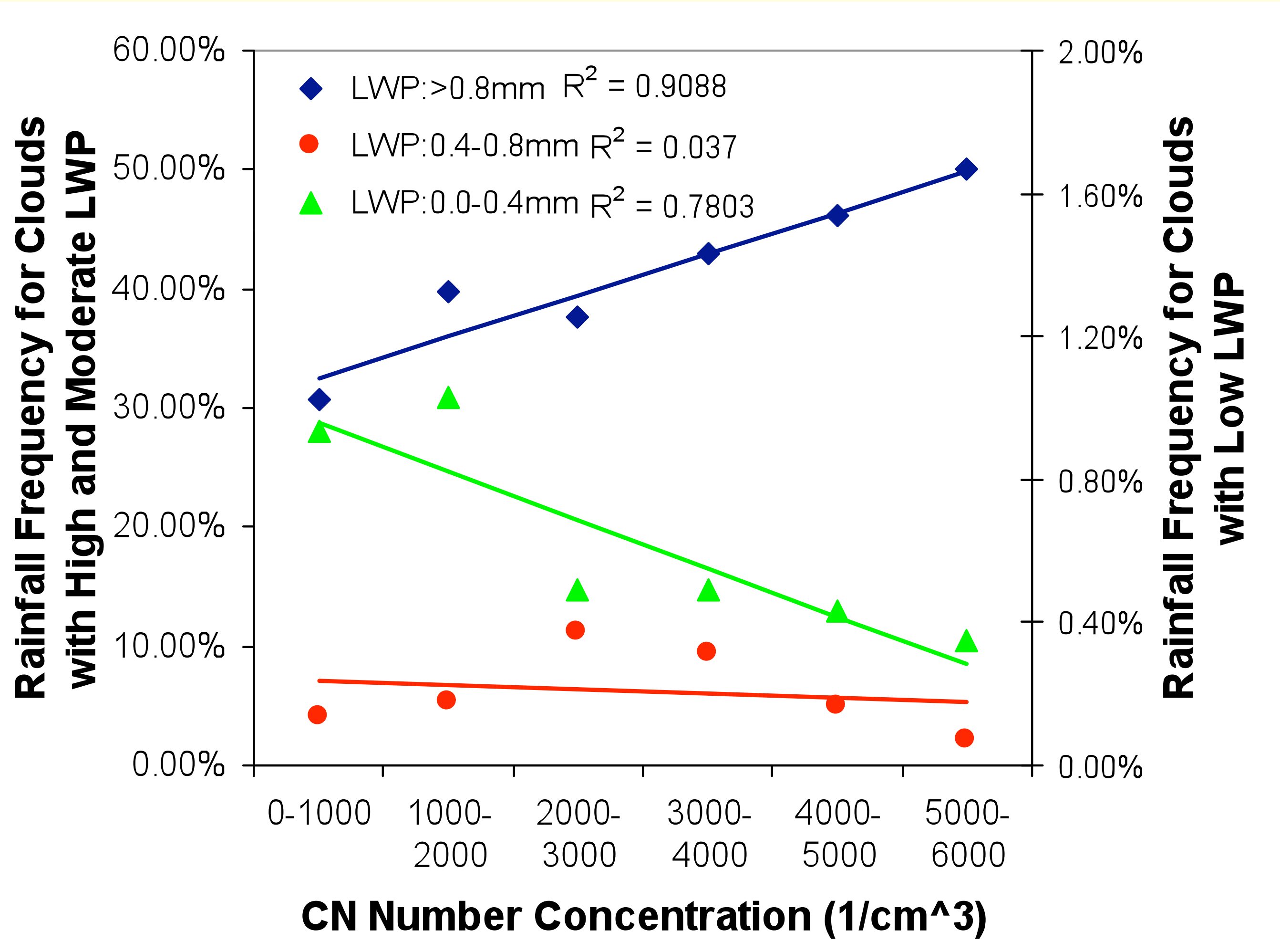
A lot have been done on the effect of aerosol on rainfall amount or intensity, but little has been done for rain frequency!

While rain amount and frequency change in harmony in general, the impact of aerosol on initiation of rain is likely to be more significant than rain amount, as the latter is dictated more by dynamics and abundance of available water

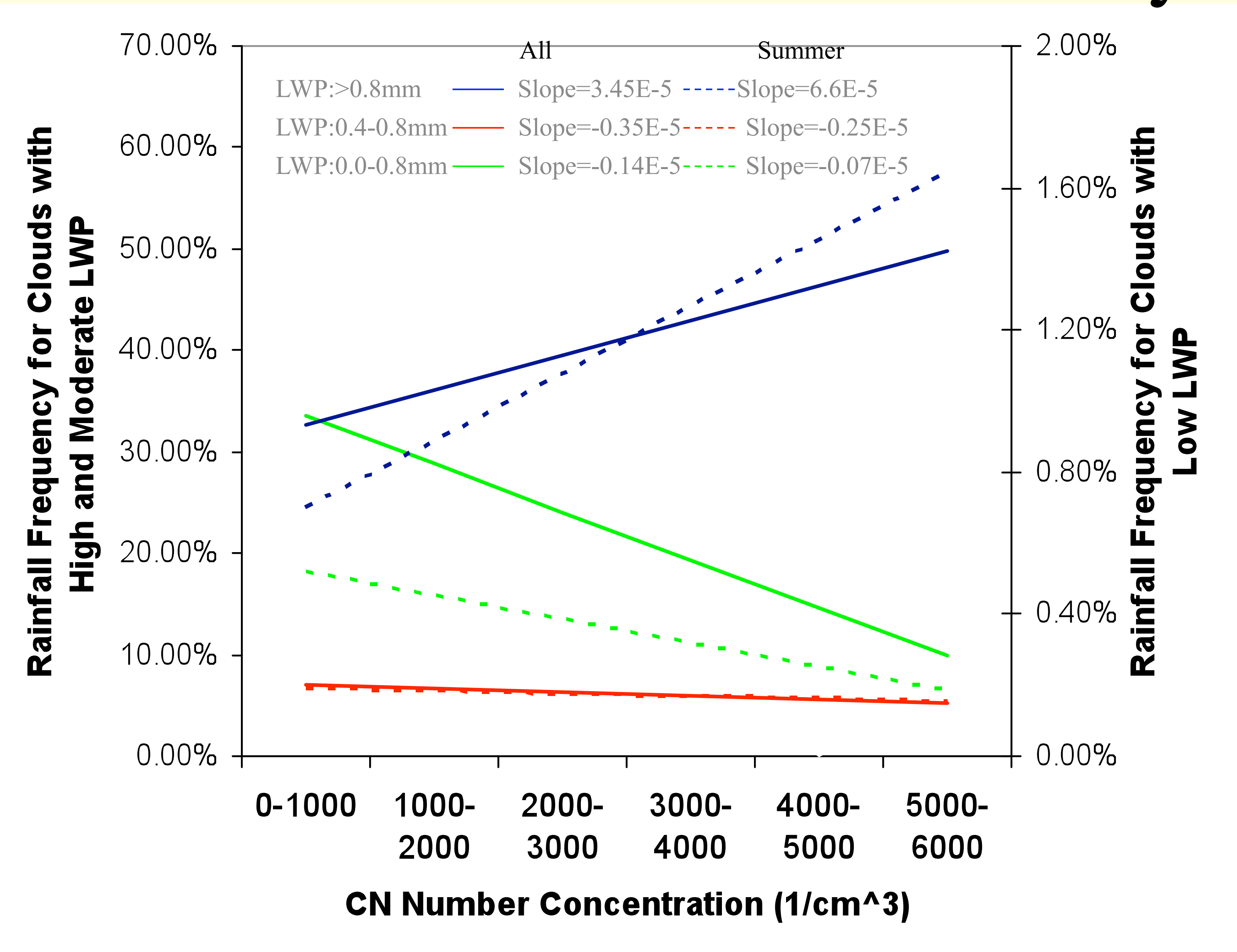
Datasets Used

- Daily ARM SGP data 2003-2008 (~20000 data samples)
- Most complete and highest quality measurements of aerosol, cloud, atmospheric state
- Key variables used:
  - Aerosol CN number concentration on the ground
  - Tipping bucket rain gauge
  - LWP from microwave radiometer
  - Cloud bottom and top heights from cloud radar & lidar
  - NOAA/NCAR Reanalysis
  - MODIS cloud particle size

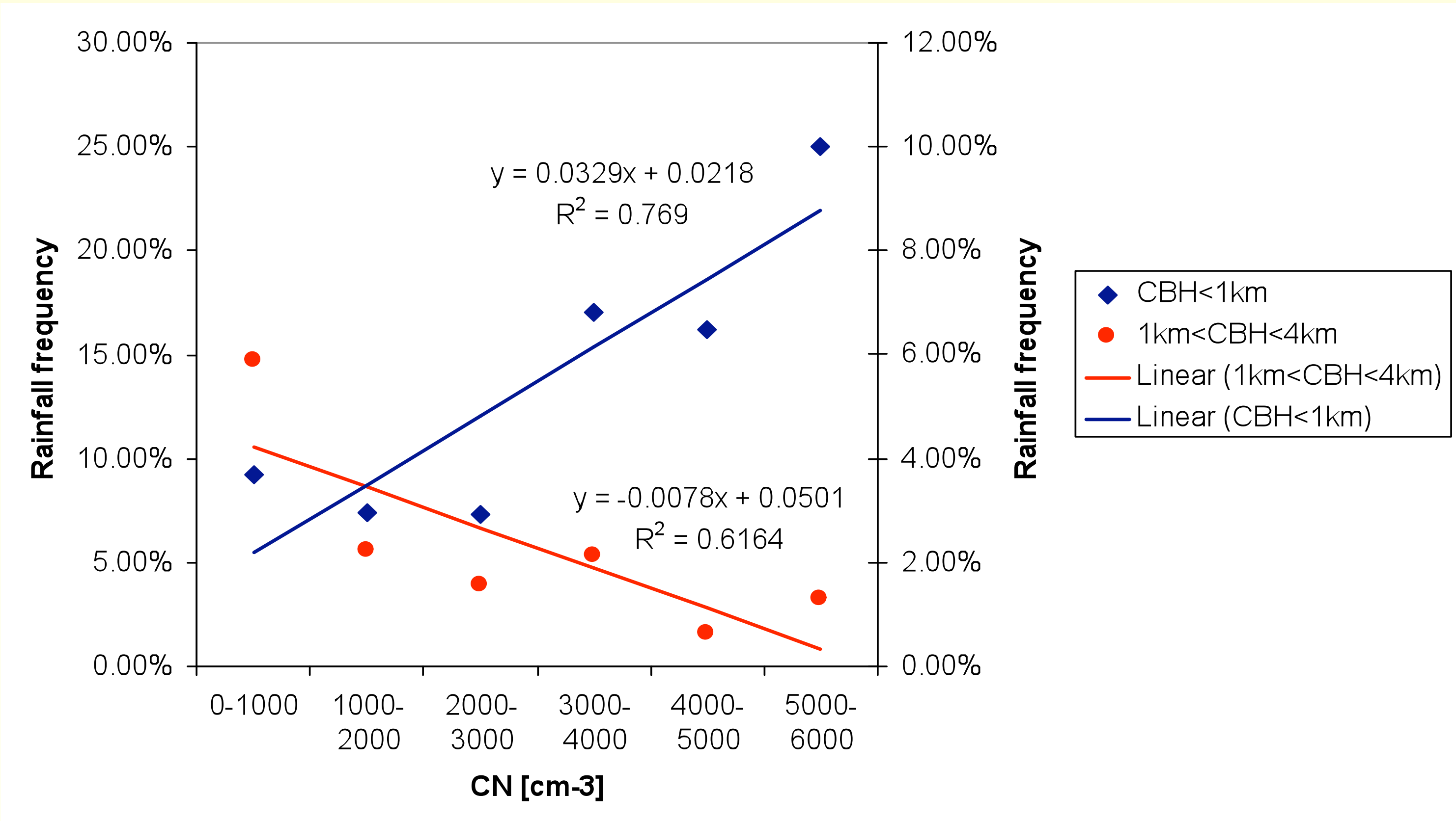
Rainfall Frequency for clouds with different liquid water path at SGP (All-Season Data)



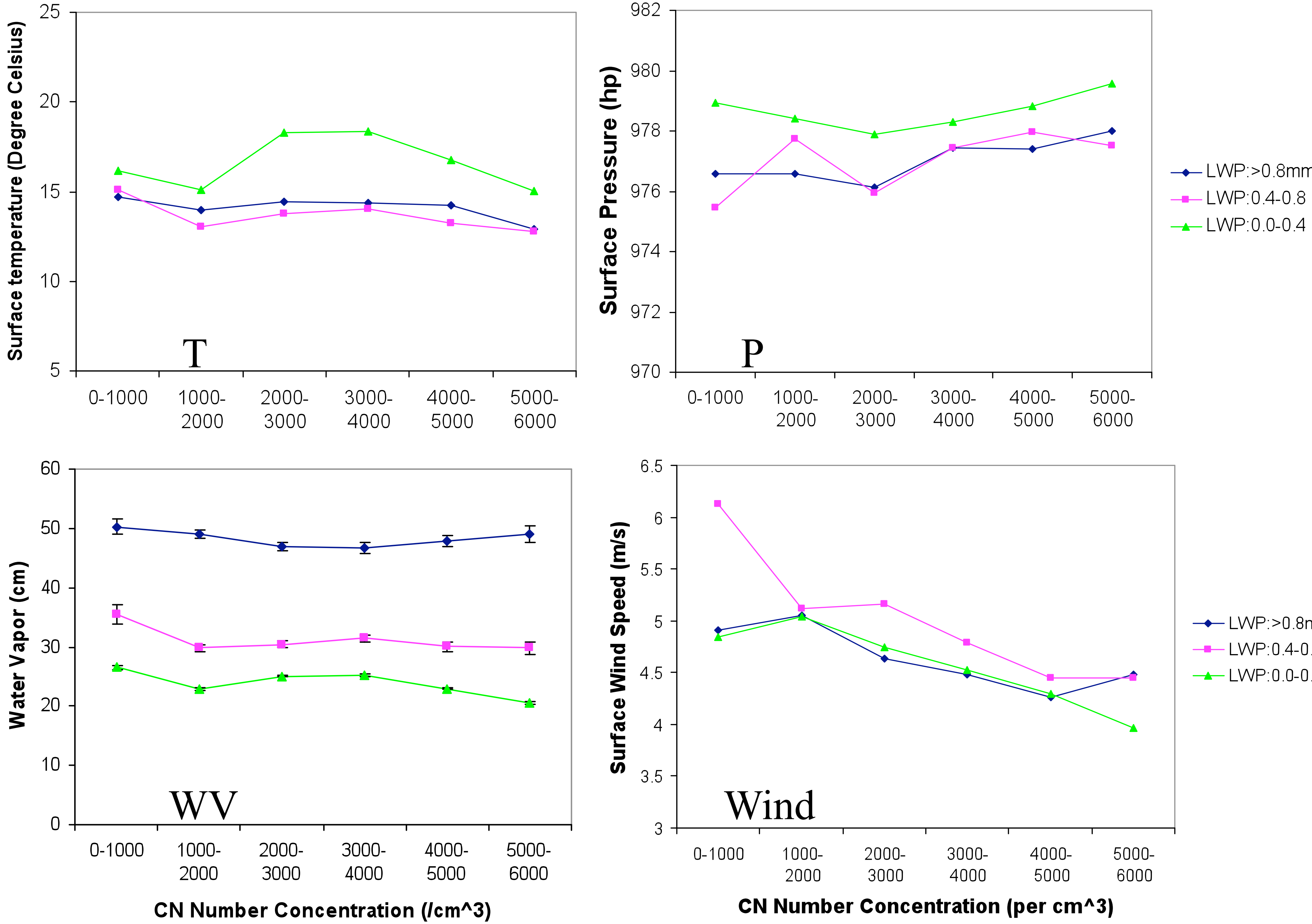
Comparison of the Results Obtained in All Seasons and in Summer Only



Summer

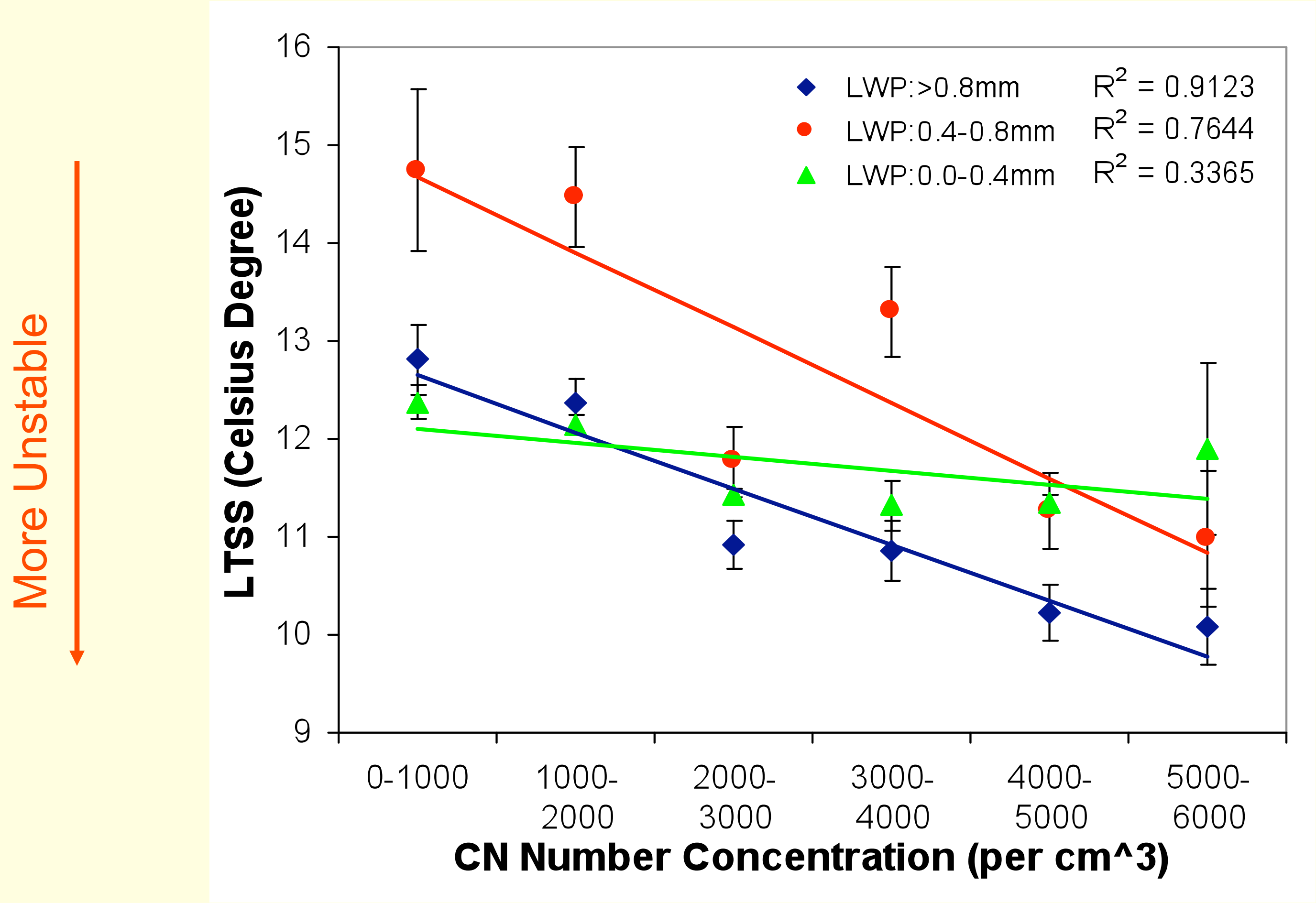


30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%
Rainfall frequency
Rainfall frequency
y = 0.0329x + 0.0218
R^2 = 0.769
y = -0.0078x + 0.0501
R^2 = 0.6164
0-1000
1000-2000
2000-3000
3000-4000
4000-5000
5000-6000
CN [cm-3]
CBH<1km
1km<CBH<4km
Linear (1km<CBH<4km)
Linear (CBH<1km)



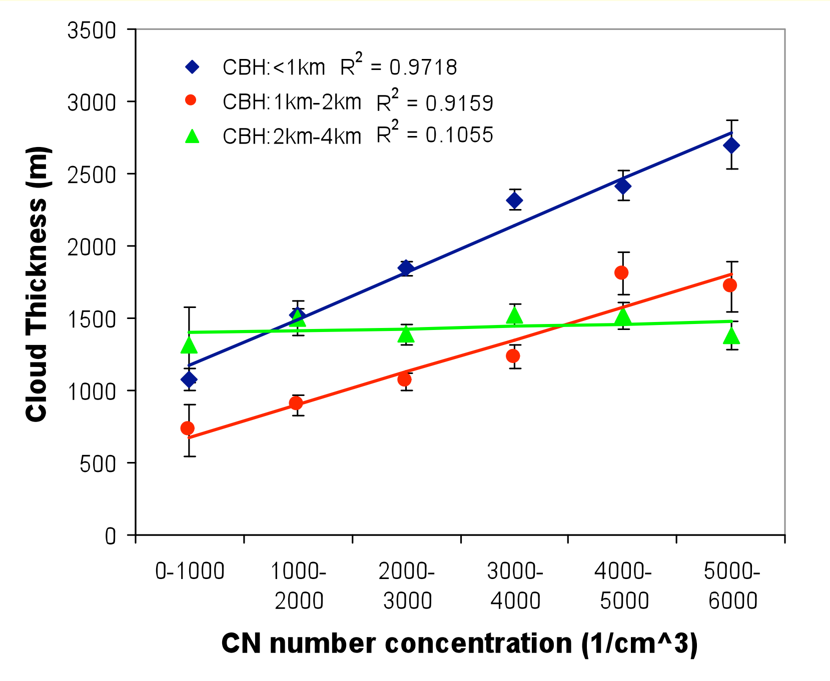
Surface temperature (Degree Celsius)
T
Surface Pressure (hp)
P
LWP:>0.8mm
LWP:0.4-0.8
LWP:0.0-0.4
Water Vapor (cm)
WV
CN Number Concentration (/cm^3)
Surface Wind Speed (m/s)
Wind
CN Number Concentration (per cm^3)
0-1000
1000-2000
2000-3000
3000-4000
4000-5000
5000-6000

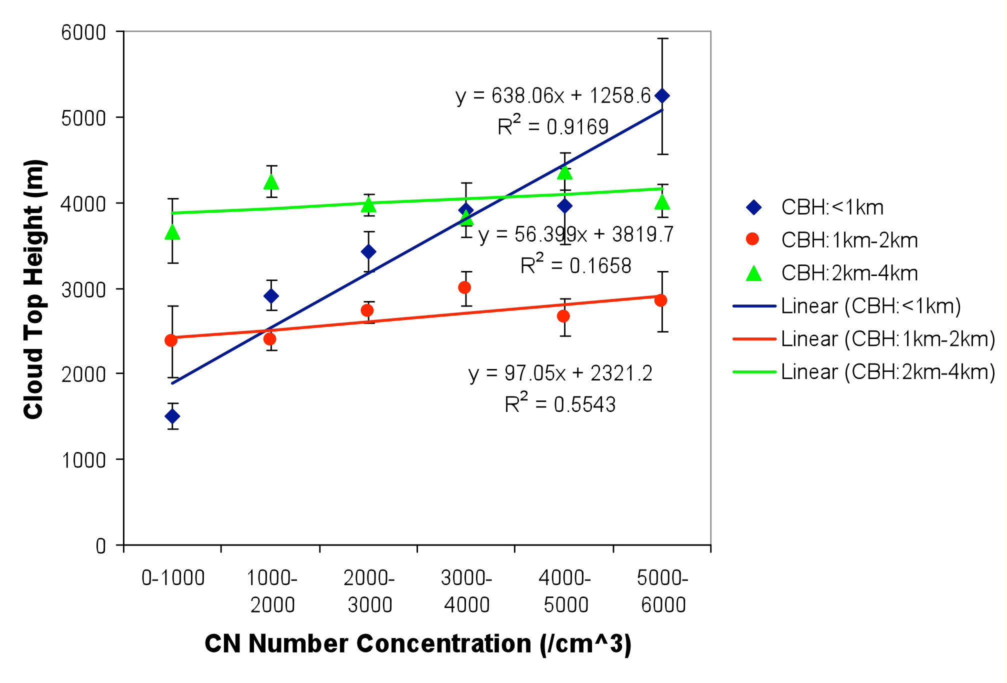
Lower Tropospheric Static Stability (LTSS)



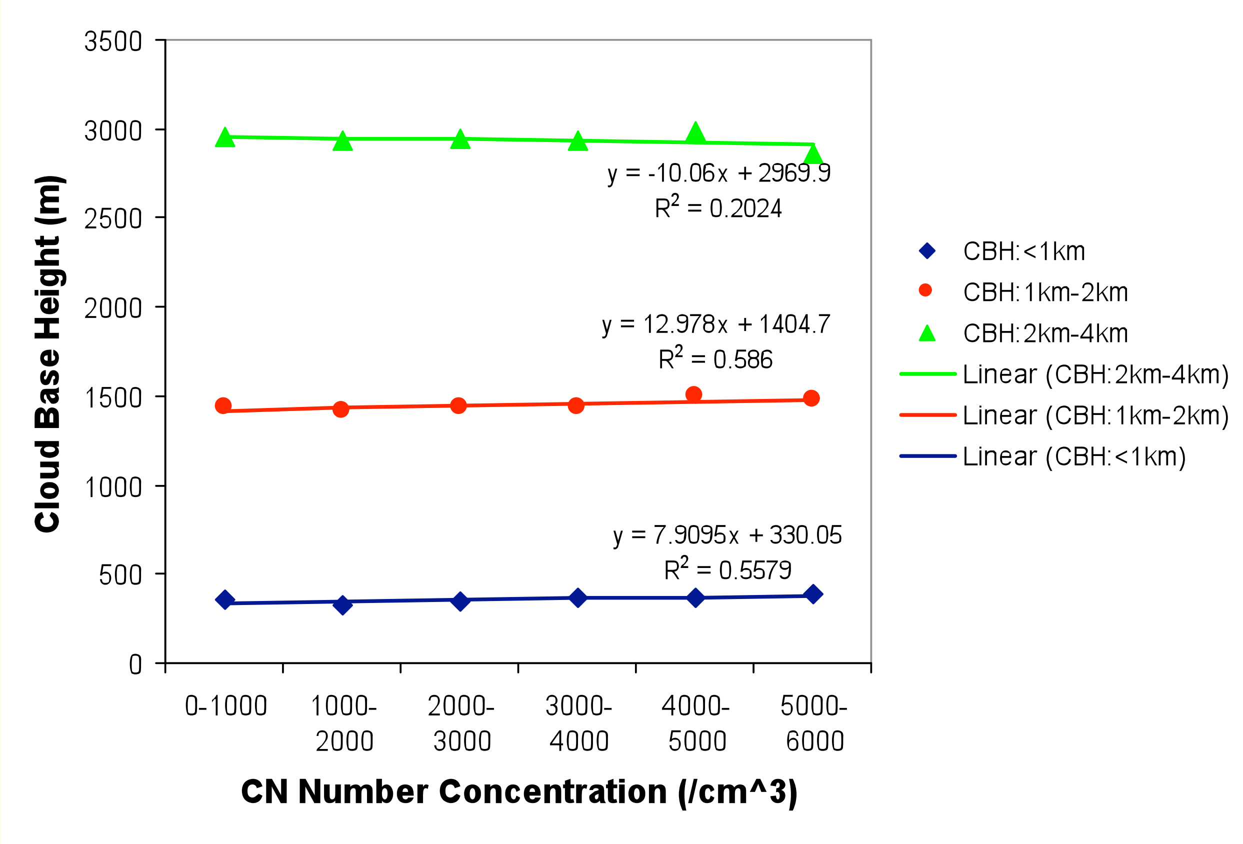
LTSS is defined as the difference of potential temperature between 700hPa and the surface [Klein and Hartmann, 1993].

Cloud Thickness and Top Height for clouds with different cloud base heights

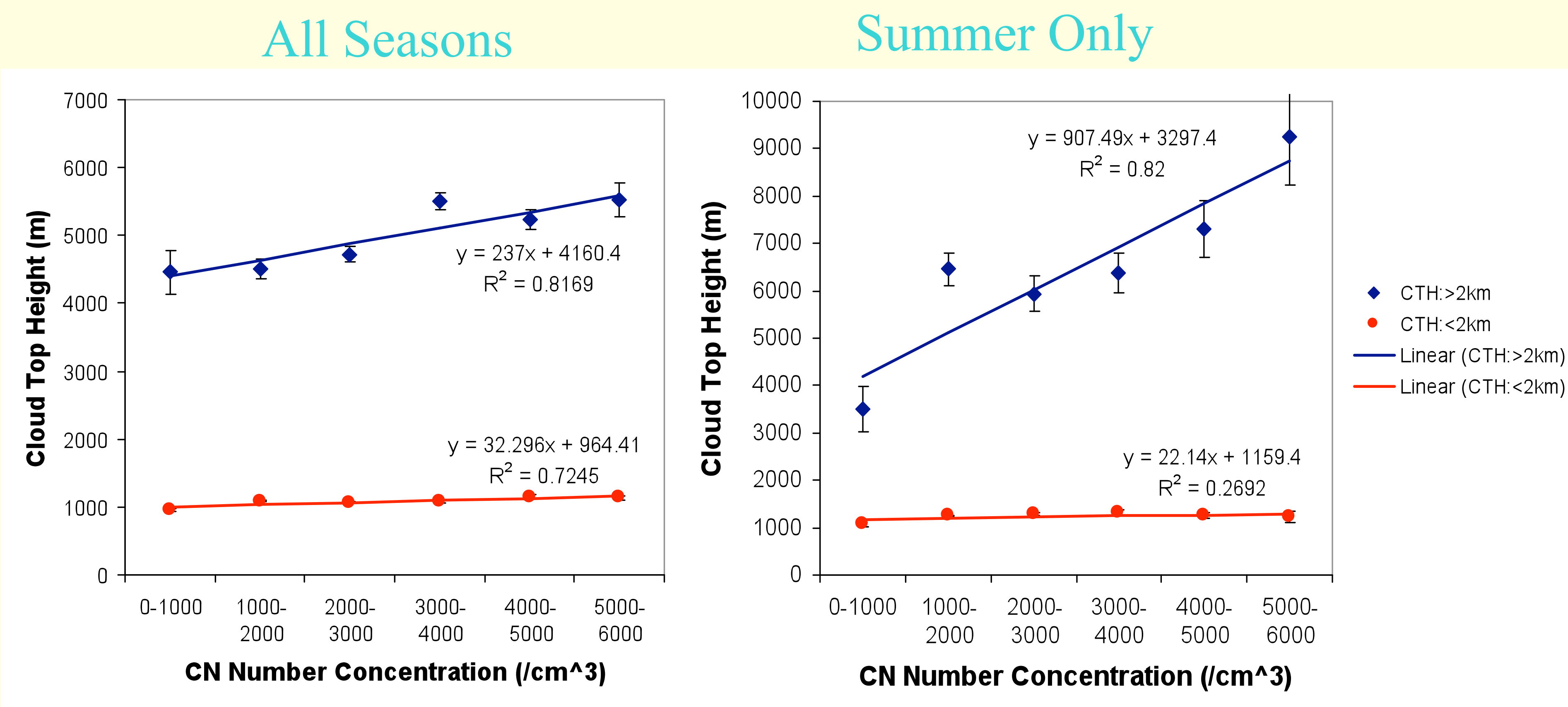




Cloud Base Heights



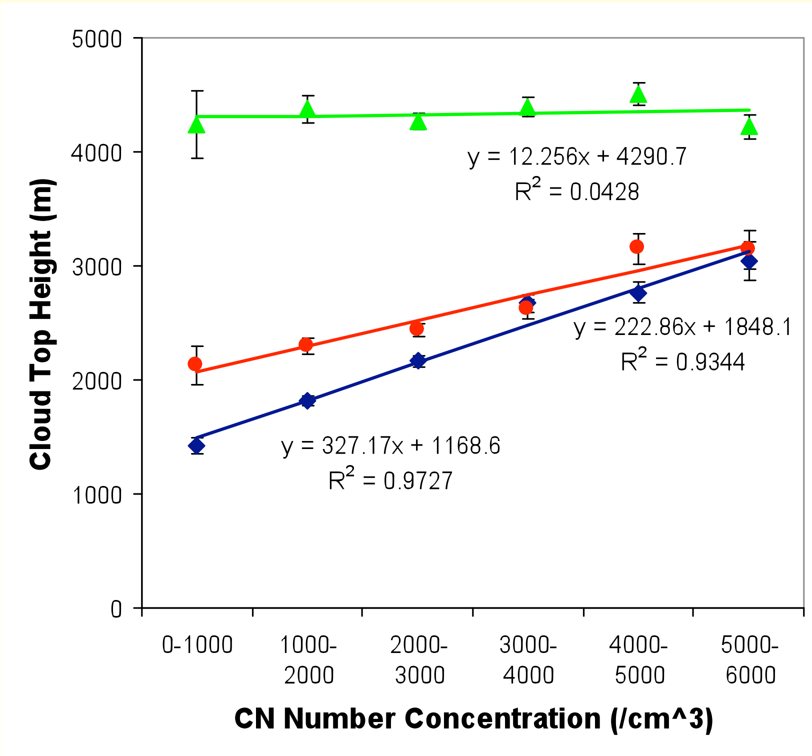
Cloud Top Heights (for clouds of cloud base <1km)



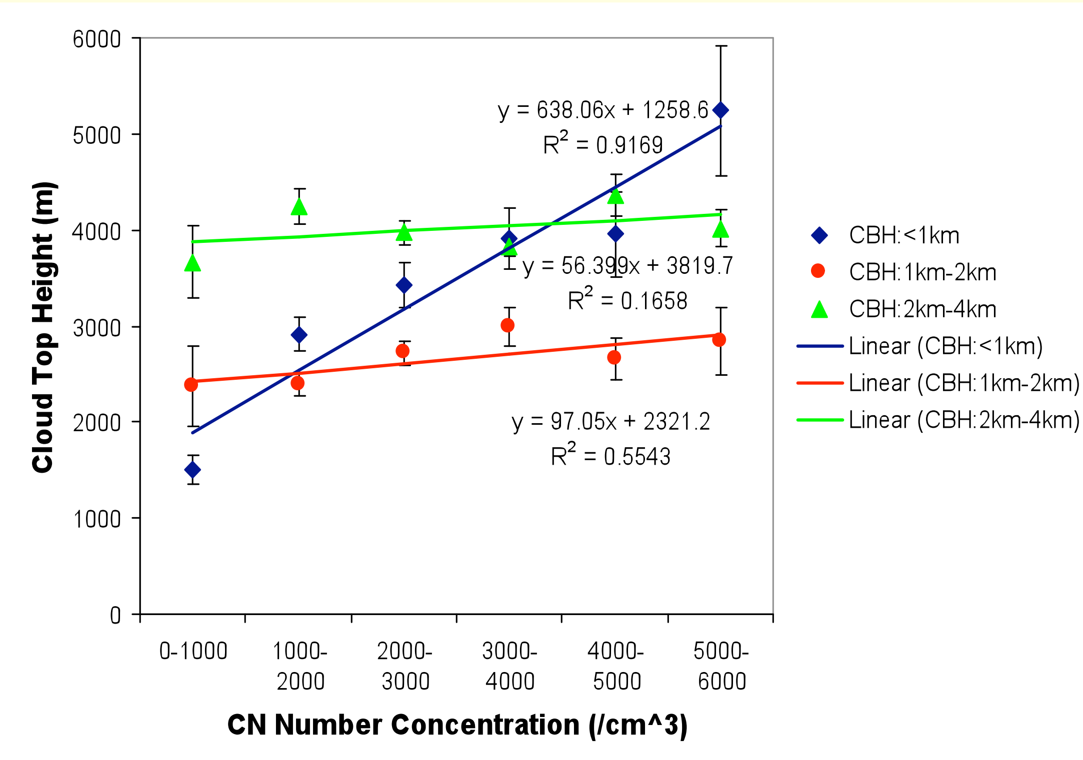
For clouds with CBH<1km, clouds are classified into two categories with cloud top heights greater (blue) and less than (red) 2km.

Cloud Top Heights

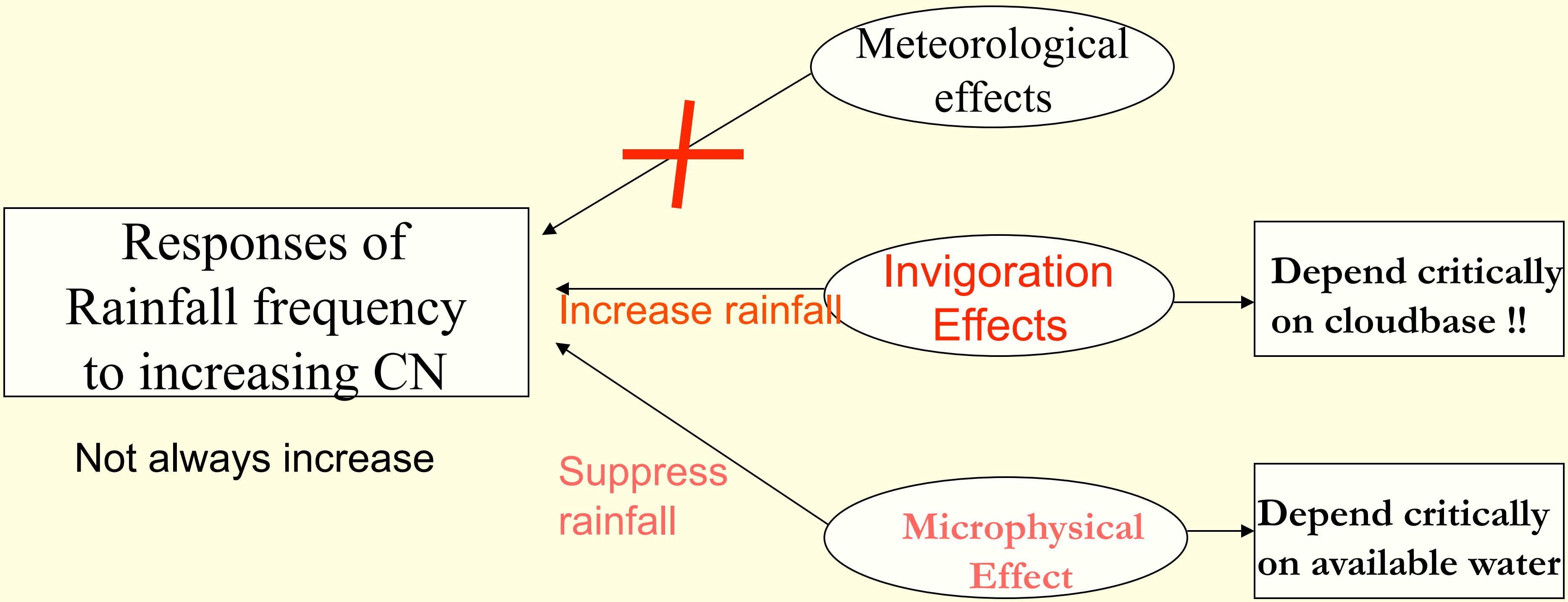
All Seasons



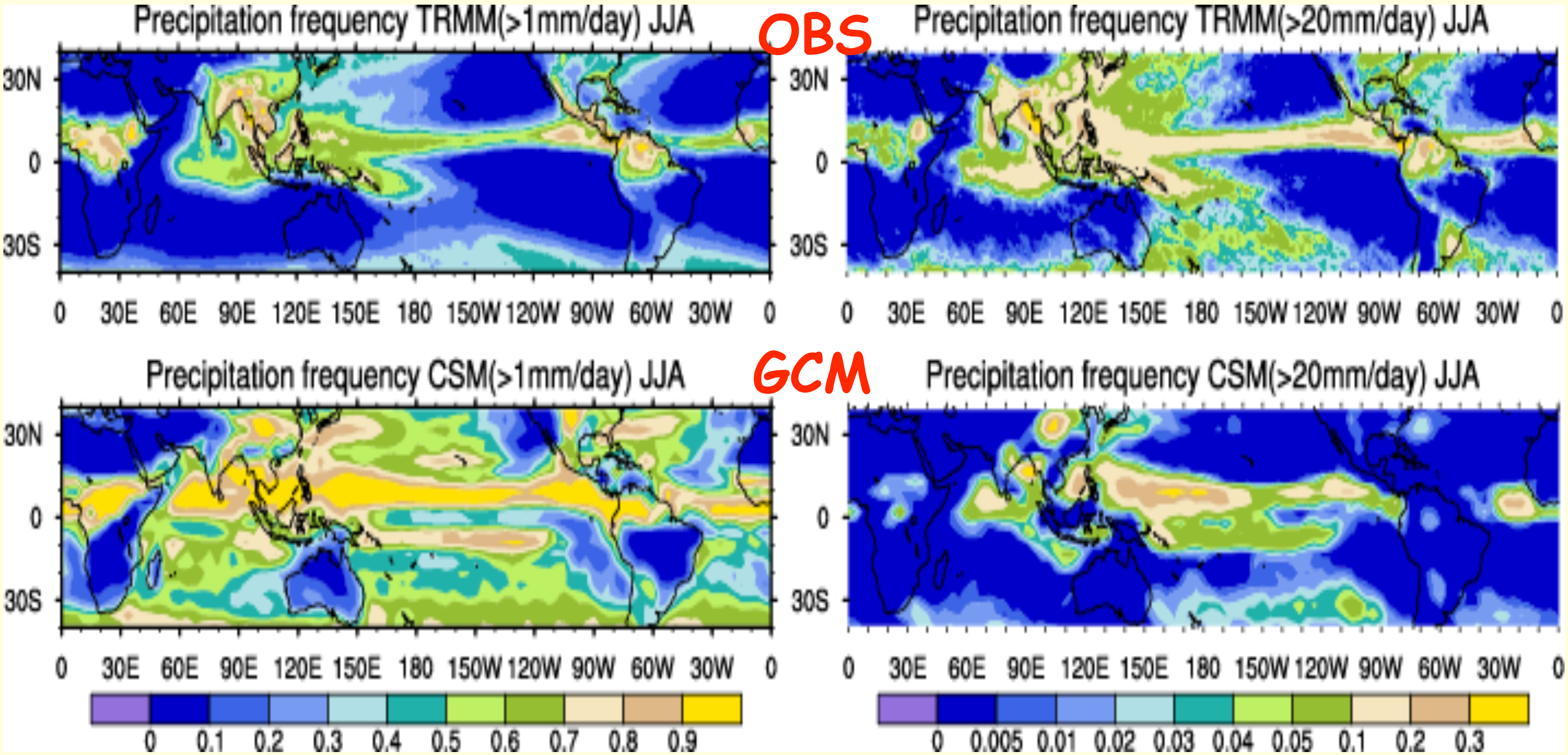
Summer Only



Competition of two opposite effects



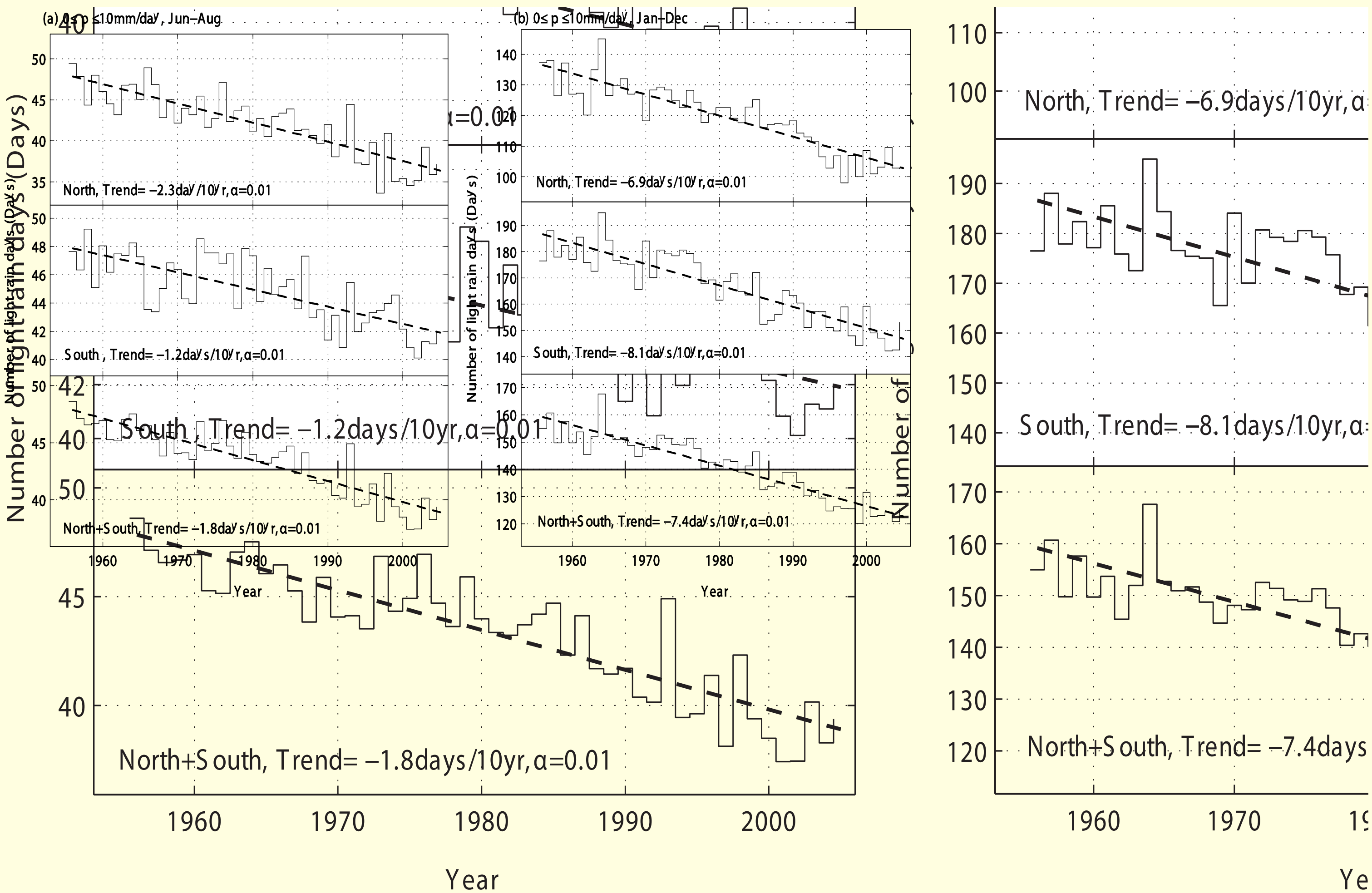
Precipitation Frequency



JJA (June, July and August) daily precipitation frequency (%)
(>1 mm day^{-1}, left; >20 mm day^{-1}, right)

Wu et al. (2007, GRL)

Time series of number of days for light rain (<10mm/day) from 1956-2005 (left: JJA; right: Jan-Dec)



Qian et al. (2009)

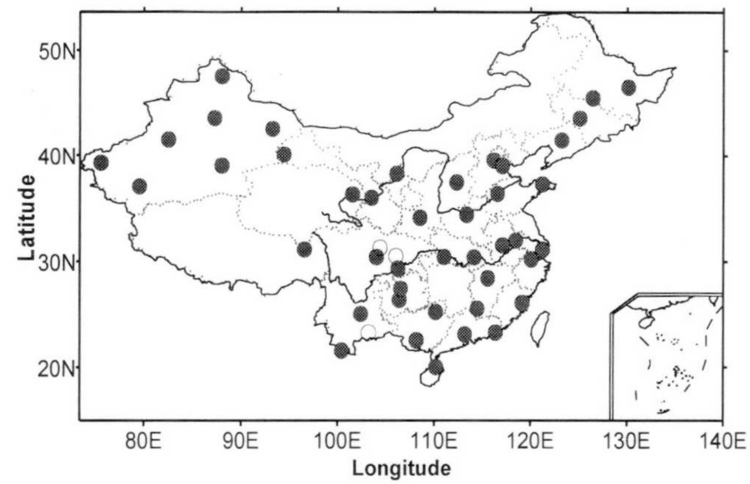


Figure 1. Locations of 46 solar radiation stations in China.

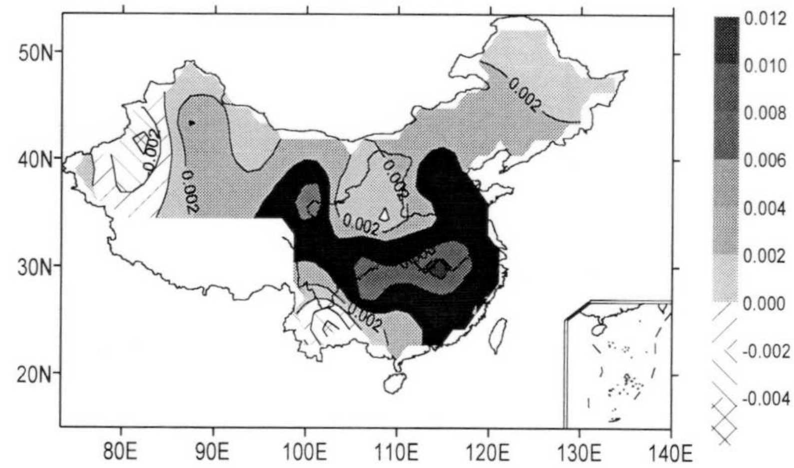


Figure 13. The linear trend （yr^{-1}） of AOD over China mainland.

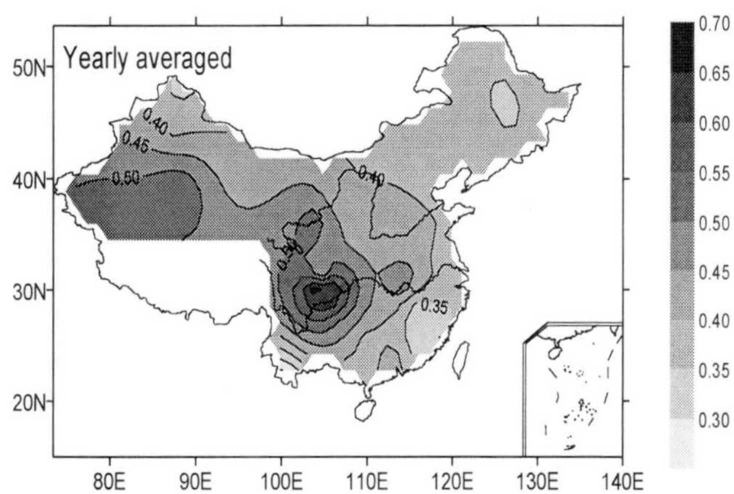


Figure 2. Distribution of multiyear mean (1961-1990) AOD over China.

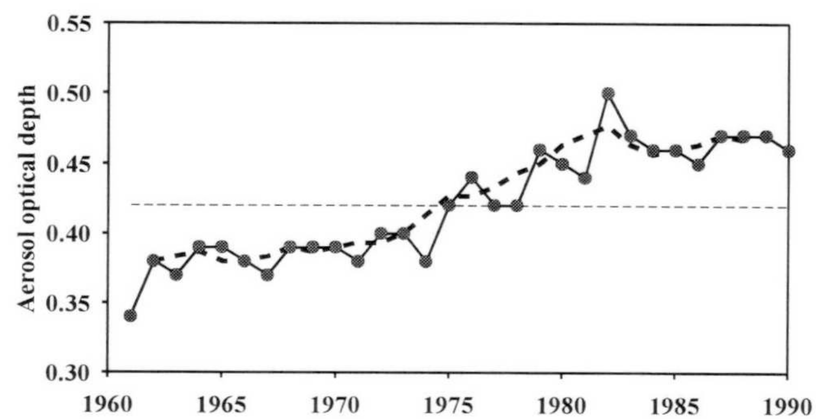


Figure 14. Yearly mean AOD variation curve of 44 stations averaged from 1961 to 1990.
(The broken line shows the three-years running average.)

Luo, 2001

ARM Mobile Facility Deployment in Shouxian

Nature (Sep 24) Feature Article on AMF-China Mission

Summary

- Aerosols appear to have very significant impact on cloud and precipitation even on *long-term mean, not just for individual cases*.
- The net impact on precipitation appear to depend on the *relative strength of aerosol microphyical effect (ME) and thermodynamic effect (TE)*.
- ME is dictated by cloud liquid water path, while TE depends critically on cloud base height.
- Cloud top height and thickness are apparently related to aerosol concentration in the PBL for low-base clouds, but no effect on high-base clouds.
- The aerosol effects are much stronger in summer than in other seasons, presumably due to its high frequency of convective clouds.